IOP Conference Series: Materials Science and Engineering

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To cite this article: Munawar A Riyadi *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **190** 012018

Development of Bio-impedance Analyzer (BIA) for Body Fat Calculation

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Abstract. Common weight scales cannot assess body composition or determine fat mass and fat-fress mass that make up the body weight. This research propose bio-impedance analysis (BIA) tool capable to body composition assessment. This tool uses four electrodes, two of which are used for 50 kHz sine wave current flow to the body and the rest are used to measure the voltage produced by the body for impedance analysis. Parameters such as height, weight, age, and gender are provided individually. These parameters together with impedance measurements are then in the process to produce a body fat percentage. The experimental result shows impressive repeatability for successive measurements (stdev $\leq$ 0.25% fat mass). Moreover, result on the hand to hand node scheme reveals average absolute difference of total subjects between two analyzer tools of 0.48% (fat mass) with maximum absolute discrepancy of 1.22% (fat mass). On the other hand, the relative error normalized to Omron's HBF-306 as comparison tool reveals less than 2% relative error. As a result, the system performance offers good evaluation tool for fat mass in the body.

1. Introduction

Household bathroom scales is commonly used for measuring body weight in everyday life. However, these scales can not distinguish between fat mass and non-fat mass (e.g. water, bones, flesh etc). Recently, the need to find out the composition of body mass, especially fat, is gaining interest due to potential health consequences behind the fat composition. Excessive fat in human body is thought to increase the likelihood of developing the disease, such as type-2 diabetes, heart problems and cancer. On the other hand, body fat deficiency could also lead to things that are not beneficial for the body [1]. The complete information of body composition would make it easier to break the pattern to maintain the health. Therefore a measurement instrument for body composition assessment that is able to distinguish fat mass and non-fat mass is deemed important and demanded [2].

Body composition assessment is divided into several categories based on the models and methods. Based on the model, there are atomic models, molecular models, cellular models, tissue-system models, and multi-component models [3]. Based on the method, it consists of underwater weighing, dilution method, dual energy x-ray absorpiometry, computed tomography, magnetic resonance imaging, neutron activation analysis, bioelectric impedance analysis, water displacement plethysmography, skinfold thickness, near-infrared measurement, waist circumference, waist-hip ratio, sagittal abdominal diameter and body mass index [1,4]. Bioelectric Impedance Analysis is one method of body composition widely used to determine body fat. This is because the BIA is easy to use, fast, noninvasive, portable and can be operated alone. It has been used in many hospitals and institutions to measure a wide variety of age ranges and conditions of the human body. In addition, BIA is also more accurate than the caliper tests, easier to use than densitometry and safer than dual energy x-ray absorpiometry (DXA) [5].

2. Method

BIA measures the composition of the human body by using the difference in the electrical conductivity of tissue. By modelling the human body into two compartments, the human body consists of fat mass (FM) and non-fat or fat-free mass (FFM) [1,6]. Fat free mass is divided into intracellular water, extracellular water, mineral bone and visceral protein as shown in Figure 1 [7]. There are differences between man and woman in terms of body composition. Generally, woman has higher percentage of fat in her body than man, while man's body usually contains higher content of minerals manifested in larger and denser bones than woman. These differences take great influence in the impedance of the body.

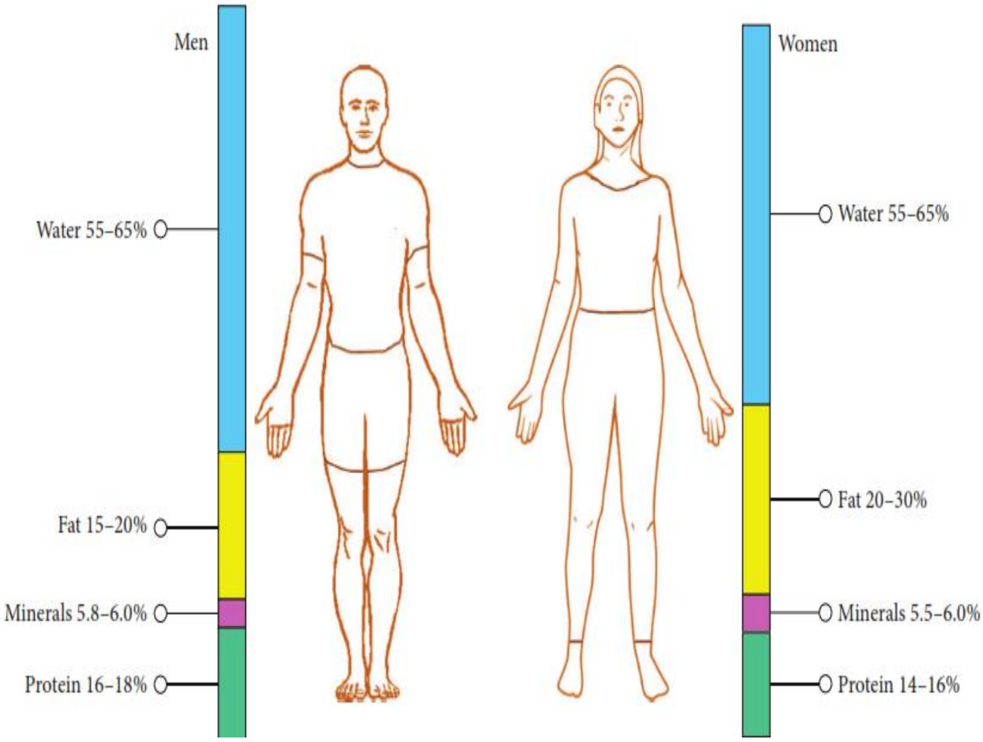

Figure 1 Differences between men's and women's human body composition [7]

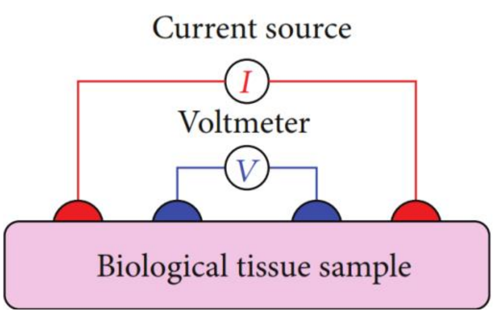

Figure 2 Concept of body impedance determination

The impedance of the body is calculated by introducing small current into the body and measuring the potential difference between two nodes on the body. Figure 2 shows the simplified concept of the impedance determination. The magnitude of current should be regulated and limited to less than 0.25 mA to avoid unwanted impact on the health of the user. It is noteworthy that the amount and variety of cells directly determine the resistance along the path taken by the current. Direct current only flow in the fluids between cells, while the alternating current can also flow through the cells, thus the cell characteristics are taken into account with this type of current [7,8]. Therefore, the alternating current (f=50 kHz) [1] was applied to be able to calculate the impedance effect in the cells.

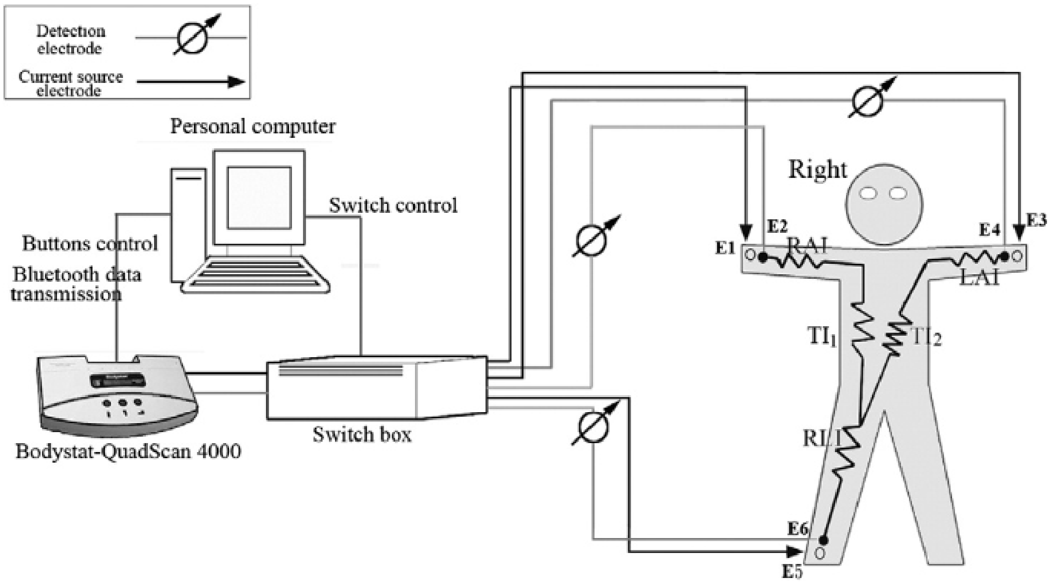

Figure 3. The measurement system of hand-to-foot mode and cross mode [4]

The simple model of body impedance network is shown in Figure 3. The model shows that different parts of the body provide different impedances. The notation of RAI is for right arm impedance, LAI for left arm impedance, TI1 and TI2 are for trunk impedances, and RLI is for right leg impedance. These impedances are influenced by many factors, including the mass of fat, and each part may provide various impedance values. Therefore, current flowing along different pairs of node into the body passes different path and eventually produces different impedance as well. For example, current flows to the body from node E1 and out from E5 passes RAI, TI1 and RLI, while current from E3 to E5 takes the path of LAI, TI2 and RLI. Consequently, the selection of current nodes and voltage detection point determines the outcome of the impedance measurement.

To determine the body fat percentage, the value of FM and FFM needs to be calculated first. FFM value is obtained by using the results of impedance measurement by the BIA correlated with empirical data for adjusting factors by considering several body parameters [9]. The value of FM is then calculated simply by using the following equation:

$$FM = w - FFM \tag{1}$$

where w is the body weight (in kg).

One published formula to calculate FFM was proposed by E. Myloot et al [6], based on the result of their experiments. In their experiments, they calculated the FFM with the comparison of BIA issued by Omron. The formula is as following:

$$FFM = 0{,}360\left(\frac{h^2}{Z}\right) + 0{,}162h + 0{,}289w - 0{,}134a + 4{,}83g - 6{,}83 \tag{2}$$

where h, Z, a and g are body height, impedance, age and gender (g=1 for man, 0 for woman), respectively. By determining the impedance, FFM can be calculated, and later the fat mass is evaluated using equation (1). Usually, the fat mass is shown in percentage over body weight.

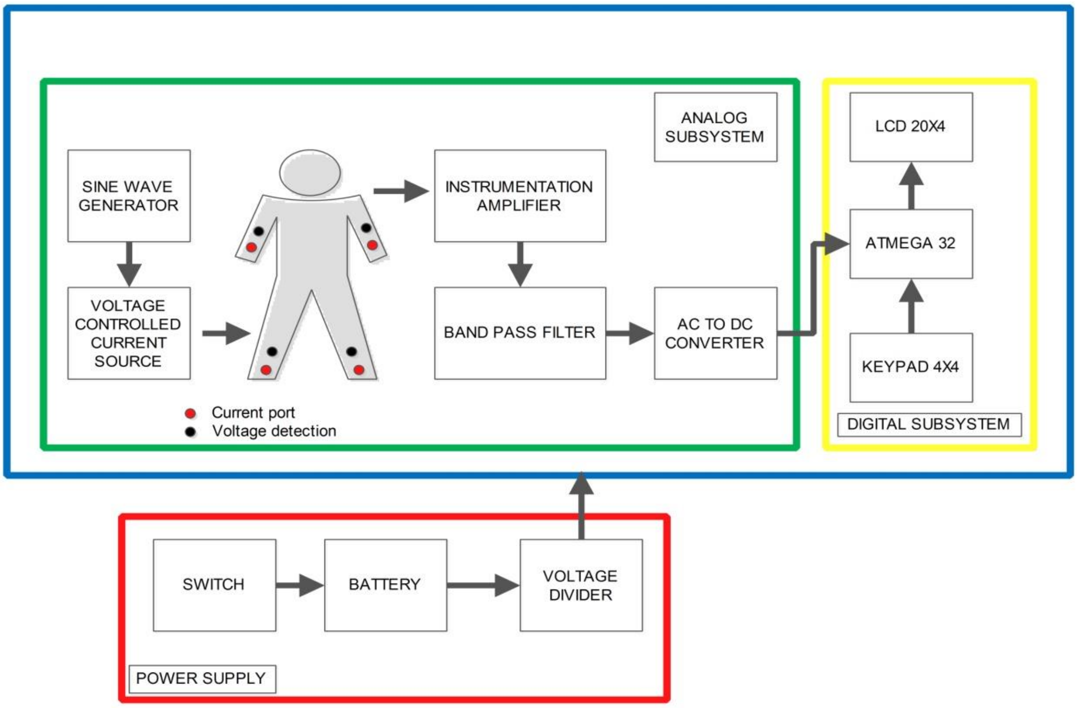

Figure 4. Block diagram of proposed bio-impedance analyzer

In order to determine the body impedance, a Bio-Impedance Analyzer was designed. The system consists of three parts, namely power supply, analog subsystem and digital subsystem blocks. Power supply consists of voltage divider, switches and batteries which provide voltage supply to the analog and digital blocks. The analog subsystem consists of sine wave generator (f=50 kHz) along with voltage-controlled current source, instrumentation amplifiers, band pass filter and AC to DC converter. This block aims to transmit currents into the human body and measure the voltage which later used to calculate the body impedance. The current source is designed to produce constant current of 0.25 mA regardless of the load impedance, in order to avoid harm to the body. The digital subsystem is ATmega32 microcontroller with 4x4 keypad and LCD functioned to control the entire measurement system. The impedance as well as body fat percentage are also calculated in this subsystem. Figure 4 shows the overall picture of the measuring system with a body fat percentage measurement method of whole body bioelectrical impedance analysis (BIA).

3. Result and discussion

The designed bioimpedance analyzer was tested on ten subjects, with equal numbers between man and woman. The subjects were of broad age range between 20-64 years old with various heights and weights as well. Their fat mass percentages were obtained using formula from equation (2), and were compared with the result from similar measurement using Omron's HBF-306. Table 1 shows the statistical analysis of repeatability of 10 repeated measurements for each subject. In addition, Table 2 shows the experimental result (P) in comparison with HBF-306 (Q), from the average of repeated measurements for each subject which consists of 10 times of repetition. For the purpose of fair comparison, the data taken were for hand to hand measurement, i.e. current ports as well as nodes are right and left arms. Although the analyzer is capable to do the impedance analysis for different pair of ports (i.e. hand to foot, foot to foot, or cross sectional analysis), the data is focused on hand to hand analysis due to the limited capability of the comparison tool, as Omron's HBF-306 can only measure hand to hand body impedance.

Table 1. Statistical analysis of fat mass percentage from repeated measurements

Subject No.	Fat Mass Percentage(%)			
	Average	Min	Max	Std Dev
1	31.07	31	31.2	0.08
2	38.19	38.1	38.3	0.10
3	20.16	20.1	20.2	0.05
4	49.43	49.3	49.8	0.16
5	44.52	44.4	44.6	0.09
6	14.35	14.1	14.5	0.12
7	15.74	15.7	15.9	0.07
8	21.27	21.1	21.5	0.13
9	37.24	37.1	37.9	0.25
10	28.08	28	28.2	0.08

Table 2. Result of *hand to hand* measurement compared to Omron's HBF-306

Subject No.	*h* (cm)	*w* (kg)	*g* (M/F)	*a* (yr)	Fat Mass Percentage		|P-Q| (%)	|(P-Q)/Q| (%)
					$P^{\#}$ (%)	$Q^{\$}$ (%)		
1	157	56	F	23	31.07	30.65	0.42	1.37
2	149	58	F	49	38.18	38.86	0.68	1.75
3	145	40	F	20	20.16	20.19	0.03	0.15
4	147	66	F	64	49.43	48.36	1.07	2.21
5	162	74	F	51	44.52	44.51	0.01	0.02
6	175	56	M	22	14.35	14.18	0.17	1.20
7	165	54	M	23	15.75	15.09	0.66	4.37
8	161	62	M	24	21.27	22.49	1.22	5.42
9	168	80	M	42	37.24	36.73	0.51	1.39
10	158	64	M	31	28.08	28.06	0.02	0.07
					Average error		0.48	1.03

$^{\#}$ *P is the result from the designed bioimpedance analyzer*
$^{\$}$ *Q is the result from Omron HBF-306*

The result shows that the analyzer was able to produce output of fat mass percentage for diverse range of input. The fat mass percentage produced by our bio impedance analyzer were in the range of 14.1 (min) to 49.8 (max) on the overall individual measurement, as indicated from Table 1. The statistical analysis also indicates that the repeatability is impressive with the maximum standard deviation of 0.25% (fat mass).

In addition, the comparison with Omron's HBF-306 shows that the average absolute difference of total subjects between two analyzer tools is 0.48% (fat mass) with maximum absolute discrepancy of 1.22% (fat mass). On the other hand, the relative error normalized to HBF-306 reveals less than 2% relative error. This means that for subject with 25% fat mass, we can confidently say that the average error only takes about ± 0.5% from the measured value. In other word, the subject's fat mass is 25±0.5%.

Analysis using hand-to-hand probes can only reveal the overall fat mass, but cannot indicate which part of body that possess more fat. The more specific analysis can be obtained by combining different measurement nodes with more enhanced calculation, as in [9]. Our analyzer is actually capable of doing the measurement from different node schemes. Other testing result shows that the average relative error rate from measurement of body fat percentage is 3.28% with right hand to right foot node, 3.15% with right hand to left foot node, 7.13% with foot to foot node, 4.73% with left hand to right foot node, and 3.89% with left hand to left foot method, all compared to HBF 306. However, HBF 306 is only for the hand-to-hand probes. Therefore, due to different node schemes between our analyzer and the comparison tools, the fat mass value obtained from all schemes other than hand-to-hand probes cannot be validated.

The experiment data shows promising data in comparison with commercial BIA. The small error found, either in the absolute or normalized error, is within acceptable value. Moreover, the usage of relatively cheap components in this system provides good alternative for evaluation of fat mass in the body.

4. Conclusion

We have designed a body impedance analyzer using single frequency, alternating current source (f=50 kHz, 0.25 mA max) with ATMega32 as primary microcontroller for calculation of body fat percentage. It is designed with the capability of fat mass analysis using several schemes of measurement, i.e. hand to hand, foot to foot, hand to foot as well as the cross sectional nodes. The experimental result indicates that the analyzer provides excellent performance for the scheme of hand to hand node, in comparison with Omron's HBF 306 as verification tool. The average discrepancy between our analyzer and the comparison tool is less than 0.5% (fat mass), or less than 2% of normalized error, within acceptable value. Other node schemes have not been validated so far due to limited capability of the comparison tool. Overall, this system shows promising performance that offers good evaluation tool for fat mass in the body.

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